

OVERVIEW ON E-XFEL STANDARD ELECTRON BEAM DIAGNOSTICS

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Abstract

The European XFEL is a 4th generation synchrotron radiation source, under construction in Hamburg [1,2]. Based on different Free-Electron Laser and spontaneous sources, driven by a 17.5 GeV superconducting accelerator, it will be able to provide several user stations with photons simultaneously. Due to the superconducting technology high average as well as peak brilliance can be produced. Flexible bunch pattern will allow for optimum tuning to the experiments demands. This paper will present the current planning of the electron beam diagnostics. An overview of the entire system will be given, as well as detailed insight into the main diagnostic systems, like BPM, charge and transmission diagnostics, beam size and beam loss monitor systems.

INTRODUCTION

The European XFEL (E-XFEL) is an international X-ray Free-Electron Laser user facility currently under construction close to DESY in Hamburg. The facility is constructed and will be operated by a limited liability company with shareholders from currently 12 counties.

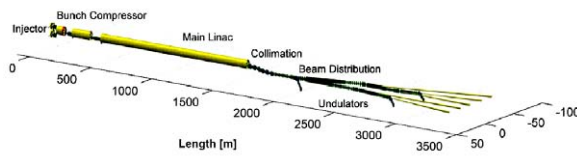


Fig. 1: Sketch of the layout of the E-XFEL.

DESY acts as the host laboratory and leads the accelerator consortium, that is in charge for the construction of the accelerator. Like FLASH [3] E-XFEL will be based on superconducting TESLA RF technology. Therefore, it can provide high duty cycles. Electron beams with pulse lengths up to 600 μ s and a bunch repetition rates up to 4.5 MHz will be accelerated up to 17.5 GeV at a RF repetition rate of 10 Hz*. The shortest FEL wavelength will be 0.1 nm corresponding to photon energies of about 10 keV. To make optimum use of the high duty cycle, the long bunch trains can be distributed into 2 SASE undulator lines, which will be ramified into additional lines for "secondary undulators" that make use of the spent beam producing either FEL or spontaneous radiation. In a first phase up to 5 beam lines can be served simultaneously. The time structure of the beam can be adjusted independently for both main SASE undulators (SASE I and SASE II) by means of a kicker/septum scheme in the beam distribution system.

* At lower gradient even higher rep rates are possible.

Table 1: Design Beam Parameters of E-XFEL

Parameter	Value	Unit
Maximum energy	17.5	GeV
normalized emittance	1-2	mm mrad
typical beam sizes (RMS)	20-200	μ m
bunch charge	0.1-1	nC
min. bunch spacing	222	ns
max. macro-pulse length	600	μ s
bunches within macro-pulse	1 - 2700	
bunch pattern	arbitrary	
RF repetition rate	< 30	Hz

The facility starts at the DESY site. Close to the HERA cryo-plant that is going to be refurbished, the injector building and the entry shaft is under construction. From this building a tunnel, 6-20 m below surface, will head towards North West to the directions of Schleswig-Holstein. After about 2 km a shaft building is located, where the main tunnel splits up into the tunnels of the two main undulators, that further down split up into the 5 undulator and photon tunnels heading towards the experimental hall, located about 3.4 km after the gun.

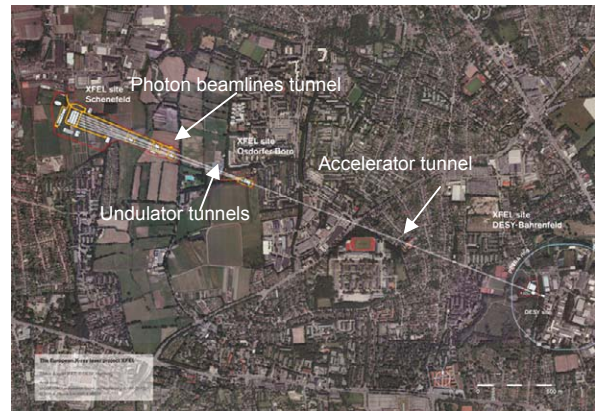


Fig. 2: Birds view of the E-XFEL site. DESY is marked by the PETRA III ring.

The current status of the facility can be described as follows: Groundbreaking for the civil construction took

place in winter 2008/2009. Tunnel boring starts in summer 2010. Tendering processes for long leading items, like the cavities, have already started. The E-XFEL company was founded in fall 2009. Currently the negotiations with all contributing labs on contracting the in-kind contributions are in their final phase.

The construction is scheduled to take about 5.5 years. According to this planning commissioning should start in 2014. SASE is expected to follow about 1 year later.

STANDARD BEAM DIAGNOSTICS

This paper focuses on standard beam diagnostics like beam position, charge, beam size and beam loss. These systems are currently in the design phase. First prototypes are available or will be constructed soon. A description of special diagnostic systems can be found in Ref. [4].

Beam Position Monitor System

The E-XFEL BPM system will be provided by a collaboration of PSI, CEA and DESY. DESY will produce the mechanics for all BPMs, except the re-entrant cavity BPMs. The BPM electronics except the front-end of the re-entrant cavity BPM, the firmware and embedded software for all BPMs will be provided by PSI. For the re-entrant cavity BPMs the monitors and the front-ends are supplied by CEA.

E-XFEL will distinguish between standard BPMs with moderate resolution and precision BPMs, where higher performance is required. For the standard BPMs the button type will be used. Precision monitors will be different cavity BPM types. About one third of the BPMs in the accelerator modules will be re-entrant cavity BPMs. About every third RF-Section of the LINAC, consisting of 4 accelerator modules, will be equipped with monitors of this type. High precision cavity BPMs with a 10 mm beam pipe will be integrated in so called undulator intersections. These are standard components, consisting of a phase-shifter, a quadrupole assembled on a xy-stage, the cavity BPM, an absorber, vacuum pump and bellows. Everything is assembled with high precision on a granite block. On this block the BPM is considered to be the element to be aligned, first by the survey and then more precisely by beam based alignment.

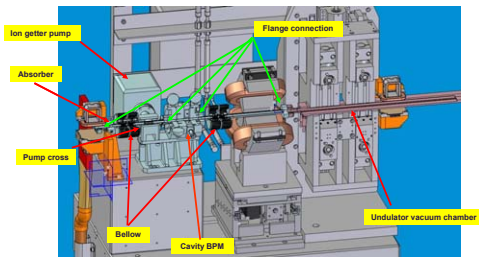


Fig. 3: E-XFEL standard undulator intersection.

In addition before and behind the undulator sections there will be some of these cavity BPMs to allow for precise beam based alignment. Further high precision (cavity) monitors with a 40.5 mm beam pipe diameter

will be used for critical sections in the machine, like the vicinity of the bunch compression chicanes, the collimation and distribution section, as well as after the undulators. This type will also be used for the Intra Bunchtrain Feedback System (IBFB) currently developed by PSI [5].

Table 2: BPM Resolution Requirements of E-XFEL

BPM Type	#	Diameter	Single Bunch Res.
Standard Button	228	40.5 mm	50 μm
“cold” BPMs	101	78 mm	$\leq 50 \mu\text{m}$
Cavity BPM	117	10 mm	1 μm
Cavity BPM	12	40.5 mm	1 μm

Button BPM

Button BPMs will be the standard BPMs for all beamlines, also in the XFEL cryo-modules. Here they are rigidly connected to the quadrupoles at the end of the accelerator module string [6].

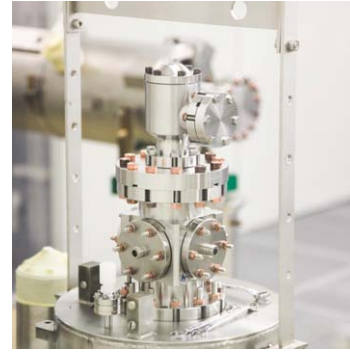


Fig. 4: Button BPM for the cryo-modules, already assembled to the superconducting quadrupole package. This monitor is part of the PXFEL3 prototype accelerator module.

The development of this BPM is almost finished. The custom made feedthroughs have passed the cryogenic tests successfully. The series production is planned to start this year.

The button BPM electronics will be based on an analogue front-end that transforms the pickups signal into a low-frequency bandwidth-limited signal of some 10ns length that are processed by a fast ADC followed by an FPGA. First prototypes are under test at FLASH and PSI.

Reentrant Cavity BPM

The re-entrant cavity BPM has the potential of better resolution compared to the standard button type [7]. From the mechanical point of view, the interfaces to the outside world of the cryo-module are identical. Also for this BPM the development is advanced. The feedthroughs are

qualified for the operation in the cold. A prototype is currently mounted in the PXFEL2 E-XFEL cryo-module prototype. The RF front-end based on a down conversion scheme with IQ detection is under development at CEA. The electronics will be integrated into the modular BPM framework developed and supplied by PSI. Beam tests are scheduled with a prototype installed at FLASH.

Cavity BPM

Two types of cavity BPMs based on the development of T. Shintake for SCSS will be used [8]. Both types with a beam pipe diameter of 10 mm and 40.5 mm, respectively, consist of a reference and dipole resonator and have very similar RF parameters. Especially the frequency of 3.3 GHz and the loaded Q of about 70 allow using the same electronics for both types. Special care is taken to minimize the orthogonal coupling of the dipole modes to the coupling slots of the dipole cavity [9]. The use of stainless steel results in rather low internal Q, preventing cross talk between consecutive bunches for all cavity modes even at the short bunch spacing of 220 ns. The design relies on precise fabrication, no tuning foreseen. Up to now all BPM prototypes have been in the tolerance of ± 20 MHz. First beam measurements are in good agreement with the simulations. The RF front-end, currently developed at PSI, will be based on down conversion and IQ detection. It will ensure high resolution and low drift.

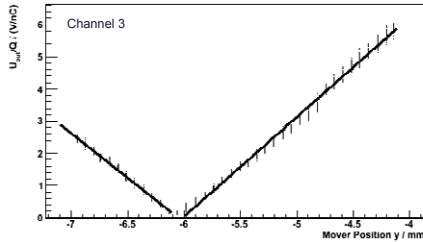


Fig. 5: Beam measurement of the sensitivity of the dipole resonator versus y-position for the 10 mm type. The sensitivity of 2.71 ± 0.3 V/nCmm agrees well with the simulation result (2.84 V/nCmm).

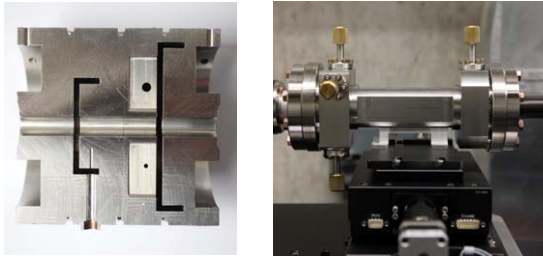


Fig. 6: Both types of E-XFEL cavity BPMs; on the left a cut through the type for the undulator sections. The right picture shows the 40.5 mm type of the cavity BPM on a precision translation stage installed in FLASH. The distance of reference (right) to dipole cavity (left) reduces crosstalk through the big beam pipe.

For extended beam tests, a BPM test section was integrated in FLASH directly after the SASE undulator. 3 cavity BPMs of the 10 mm, and one of 40.5 mm type are mounted on high precision translation stages, to allow for precise calibration and resolution measurements. In addition there is also an array of 3 button BPMs similar to the E-XFEL standard beam pipe BPMs. All signals are available over short cables outside the FLASH tunnel.

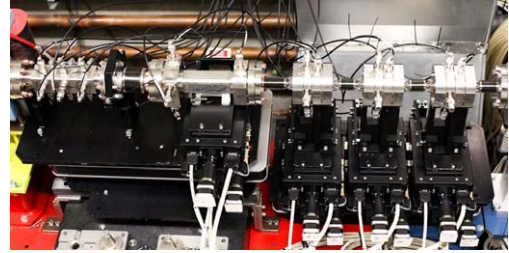


Fig. 7: E-XFEL BPM test section in FLASH.

BPM Electronics

The overall BPM electronics system follows a modular design approach maximizing the amount of commonly used hard- and software for all BPM types. The BPM electronics consists of analogue RF front-ends (RFFE) specific for each pickup type, and a generic FPGA-based digital back-end carrier board with two ADC mezzanine modules. The RFFEs and the digital back-end board with its ADC mezzanine modules are plugged into a common customized crate that contains one generic digital back-end as well as either four button BPM RFFEs or two cavity or re-entrant BPM RFFEs.

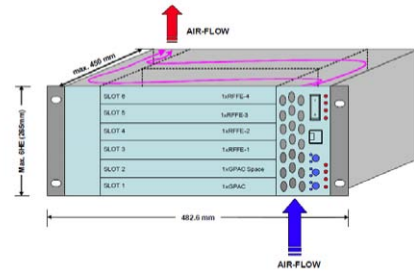


Fig. 8: Picture of a BPM electronics unit for E-XFEL.

This generic modular hardware approach is also employed for the IBFB-specific low-latency BPM and signal processing hardware[10] allows minimizing the overall development and maintenance effort and provides a unified control and timing system interface for all BPMs in the machine.

XFEL CRATESYSTEM

E-XFEL will use xTCA systems as the crate standard. A special group was created to extend the xTCA standards for physics purpose [11]. According to these extensions XFEL will use double size AMC boards. Two standard boards for XFEL are currently under development, a commercial 16 bit 125 MHz ADC with 10

channels, and an in house developed versatile interface board with 4 fast serial links (DAMC02) [12]. Both boards supply a high amount of processing power due to a VIRTEX 5 FPGA on board.

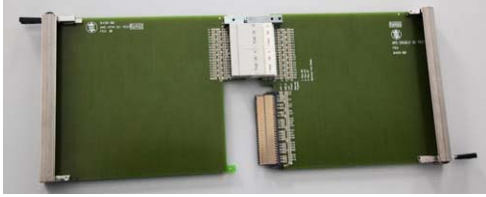


Fig. 9: Double sized AMC “dummy” board with a rear transition module (RTM).

For extended IO purpose the boards can be extended by so called rear transition modules (RTM), again doubling the space for the electronics. Different applications will be adapted to these boards by means of special RTMs. The diagnostics will make use of these boards with special RTMs for toroids, wire-scanners and beam loss monitors.

BEAM SIZE MEASUREMENTS

For all SASE machines the optimisation of the emittance transport is essential for the FEL performance. E-XFEL will have special diagnostic sections after the injector, the two bunch compressors and in the collimation section to measure the projected and the slice emittance. These stations will combine 4 beam size measurements to determine the local twiss parameters as well as the emittance. This allows controlling the optics and matching to the next sections.

Up to the second bunch compressor the beam size measurements will be done by means of OTR screens. These screens will include on axis and off axis OTR targets. The off axis targets will be used in combination with kicker magnets deflecting a single bunch out of the 650 μ s long bunchtrain onto the screen. In addition this bunch can be streaked by a transverse mode structure to get access to slice parameters [4]. Resolution of the OTR stations has to be between 30 and 10 μ m depending on their location. Since LCLS has reported problems with coherent effects with their OTR systems due to the strongly compressed beam [13], the E-XFEL OTR chambers provide ports to install additional wire scanners.

On-axis and off-axis operation requires different focal spots. In addition the imaging of a streaked beam requires large field of view. Both aspects are tackled by the use of Scheimpflug’s principle, known from large format cameras. It allows extending the depth of field by choosing appropriate angles between the object, the image and the lens plane. If these planes have a common intersection line, the entire screen plane is imaged well focused onto the image plane. An angle of 67.5° between beam axis and screen surface was chosen. A magnification close to 1:1 has to be used to achieve the required resolution. With large view fields large CCD chip cameras will be required.

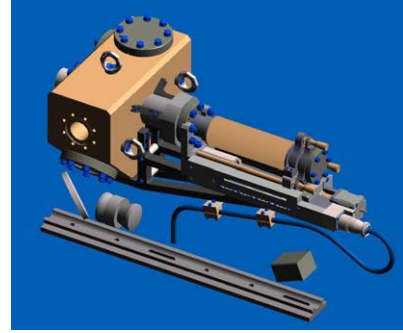


Fig. 10: 3D view of an E-XFEL OTR station. Due to the angle with the beam the OTR is emitted under 45° in backward direction. Scheimpflug’s principle is drafted by the tilted camera box. The blind flanges are the ports for the wire-scanners.

Due to the small beam size in the high energy sections wire scanners will be used for measurements. They have to provide fast scans, i.e. the wire is driven through the beam during one RF-pulse with a speed of 1 m/s. The technical progress allows using linear motors. The trigger of a scan has to be precisely synchronized to arrival of the beam. A prototype has shown a trigger jitter of less than 10 μ s, corresponding to a position or bunch number jitter of less than 10 μ m or 10 bunches.

CHARGE MEASUREMENT

To ensure proper beam transport the transmission has to be close to 100%. Therefore the bunch charge has to be measured at various places along the LINAC. Furthermore, charge has to be well controlled for stable SASE operation. The current transformers (toroid) will be of the same type already in use at FLASH. The electronics will be based on the DAMC02 μ TCA/RTM boards with fast sampling ADC and FPGA post-processing. Single toroids will be linked to their neighbours by fast optical links to release alarms to the machine protection system with few μ s latency in case of imperfect transmission. A fast link to the LLRF will provide charge information for beam loading compensation.

DARK CURRENT

With the long RF pulse trains of the superconducting LINACs dark current suppression is essential. The biggest source of dark current is the normal conducting RF gun with a gradient up to 60 MV/m. Electrons emitted there might be transported through the entire facility. At FLASH dark current is one main source for activation of machine components. Monitoring dark current is substantial for optimizing the suppression systems.

Therefore, a dark current monitor based on a 1.3 GHz stainless steel cavity similar to the reference cavity of the cavity BPMs was developed [14]. Prototypes are installed at FLASH and PITZ. First measurements are expected

this spring. These sensitive monitors are also suited for charge measurements in case of very low charge operation of FLASH or E-XFEL.



Fig. 11: 1.3 GHz cavity dark current monitor with one coupling antenna in front.

BEAM LOSS AND MACHINE PROTECTION

The superconducting E-XFEL LINAC is able to transport about 600 kW CW beam power at 17.5 GeV. Thus a machine protection system (MPS) is essential to prevent the machine from mechanical damage, but also to minimize activation and radiation damage.

The MPS will be an upgraded version of the FLASH system [15]. Slow signals from magnets, RF, vacuum and screens will be used to check for the correct machine state and will block beam operation or allow for only single or few bunches depending on the status of the machine. Fast signals from beam loss monitors or transmission measurements will interrupt the bunch train. The logic units collecting, communicating and evaluating the input channels and creating the alarms will be implemented in the FPGA of the DAMC02 μ TCA board [16].

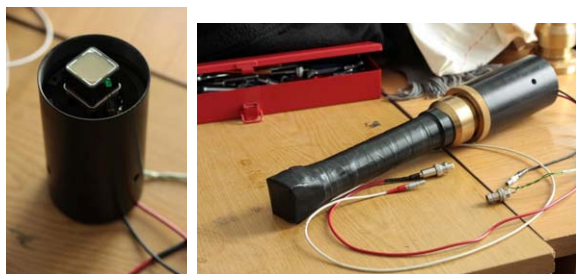


Fig. 12: First prototype of an XFEL BLM. On the left a view to the photomultiplier with the test LED, on the right a test setup to be installed in FLASH. The goal is a compact design.

The beam loss monitors will be based on photomultipliers. The monitors itself will be produced by IHEP, Protvino, the electronics will be developed and produced at DESY. The BLM readout will also base on the DAMC02 hardware. The signals from 8 monitors will be processed by one readout unit. The shaped data from the BLM is digitized by 14 bit 50 MHz ADCs located on

a RTM, integration of losses and alarm generation is done in the FPGA of the DAMC02 board. The latency of the system is about 300 ns plus cable delay. A second μ TCA board produces the test signals to drive the LED implemented in the BLM.

SUMMARY

The developments for the standard beam diagnostics for E-XFEL are in an advanced state. The design of the main systems is clear, and partners within E-XFEL collaboration are fixed. First prototypes are already under test at FLASH.

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